Publications of the Astronomical Society of Japan Advance Access published October 28, 2014

Publ. Astron. Soc. Japan (2014) 00 (0), 1–5
doi: 10.1093/pasj/psu084
Advance Access Publication Date: 2014 0

Morphological study of penumbral formation

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Received 2014 February 14; Accepted 2014 March 24

Abstract

Penumbrae are known to be areas of mainly horizontal magnetic field surrounding umbrae of relatively large and mature sunspots. In this paper, we observationally studied the formation of penumbrae in NOAA 10978, where several penumbral formations were observed in *G*-band images of the Solar Optical Telescope on board Hinode. Thanks to the continuous observation by Hinode, we could morphologically follow the evolution of sunspots and found that there are several paths to the penumbral formation: (1) active accumulation of magnetic flux, (2) rapid emergence of magnetic field, and (3) appearance of twisted or rotating magnetic tubes. In all of these cases, magnetic fields are expected to sustain high inclination at the edges of flux tube concentration longer than the characteristic growth time of downward magnetic pumping.

Key words: convection — Sun: magnetic fields — Sun: photosphere — sunspots

1 Introduction

Well-developed sunspots are fledged with surrounding penumbrae. The magnetic field in the penumbral area is known to be nearly horizontal (Stix 2002). The formation mechanism of penumbrae has been studied by many authors theoretically or observationally (Borrero & Ichimoto 2011; Rempel 2011, and references cited therein).

Rucklidge, Schmidt, and Weiss (1995) studied the energy flows in a model sunspot including the lateral energy flux from the surrounding inclined magnetic field, and showed that sunspot MHD structure has two equilibrium states (pores and sunspots) and that the structure will change abruptly or transit from pore state to sunspot state when the inclination of the surrounding magnetic field gets larger than a threshold value. Succeeding numerical simulations by Hurlburt and Rucklidge (2000) and Tildesley and Weiss (2004) led to the idea of a downward magnetic pumping mechanism around sunspots (Weiss et al. 2004). Cheung et al. (2010) and then Rempel (2012) closely studied the necessary chromospheric boundary conditions for extended penumbral formation.

Observationally, Shimizu, Ichimoto, and Suematsu (2012) detected a case of penumbral formation where the appearance of a chromospheric dark annular zone, which may correspond to a horizontal magnetic field, precedes the formation of photospheric penumbra. The work inspired us to observationally follow the evolution of penumbral structure in many varieties of sunspots, continuously in time, with the Solar Optical Telescope (SOT) on board Hinode (Suematsu et al. 2008; Tsuneta et al. 2008).

In this paper, we observationally studied the formation of penumbrae in NOAA 10978, where several penumbral formations were observed in *G*-band images of SOT/Hinode. We will briefly report that there are several paths where the surrounding magnetic fields of sunspots are inclined and eventually lead to the formation of penumbrae.

2 Morphological study of penumbral formation in NOAA 10978

NOAA 10978 was a very large sunspot group, covered a wide area on the solar surface, and showed several active emerging flux regions (EFRs) which developed to form sunspots with penumbrae. Figure 1 shows white light and magnetic maps of the region on 2007 December 12. Flux emergence in the region was very active from December 11 through 13. From visual inspection of the *G*-band movie, we selected three sub-regions as examples of different paths of penumbral formation.

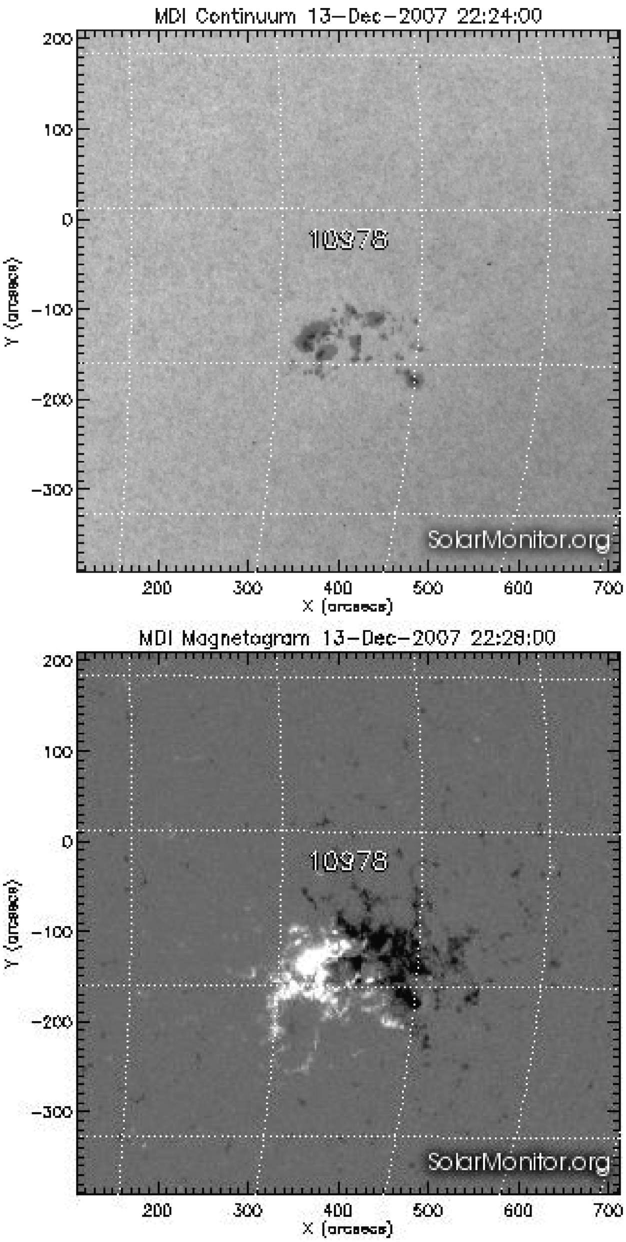

Fig. 1. NOAA 10978 on 2007 December 12. Top: White light image. Bottom: Map of line-of-sight magnetic field. Courtesy of SolarMonitor.org.

2.1 Active accumulation of magnetic flux

In figure 2, we show a case of penumbral formation due to rapid accumulation of magnetic flux. The accumulation continued for around 40 hr in this case until the formation of fully developed penumbra. Let us simply assume that

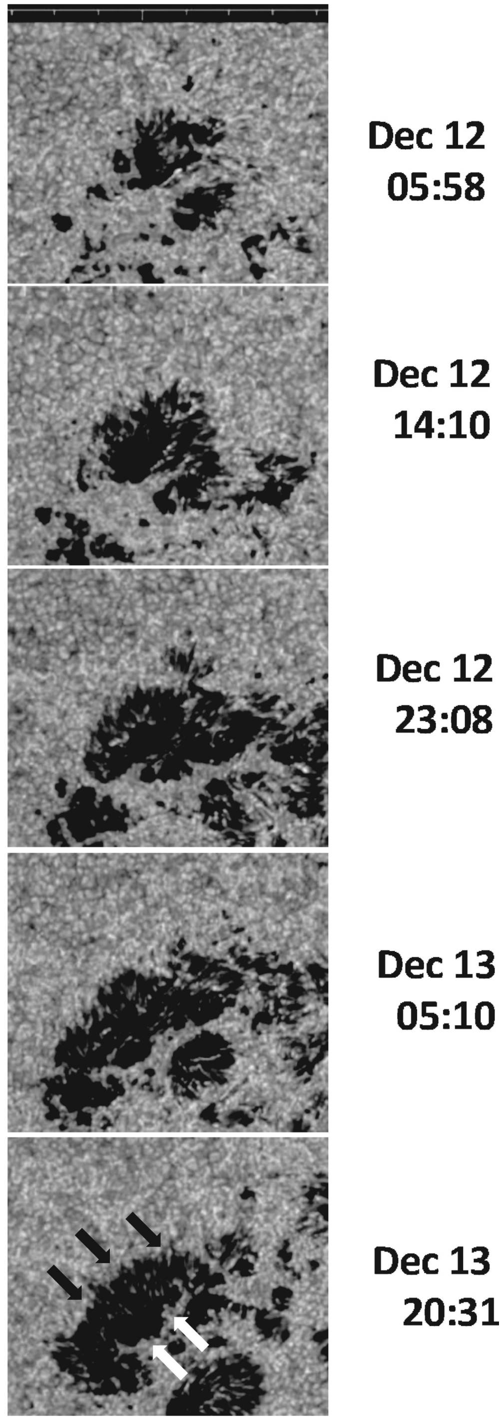

Fig. 2. Rapid accumulation of magnetic flux. The polarity over the area is positive. Black arrows indicate the penumbral area, while white arrows show the umbra/photosphere boundary without penumbral structure. The FOV is about 75″ × 66″.

the magnetic field of a sunspot takes a canopy structure due to the force balance between the inside magnetic pressure and the outside gas pressure. When the magnetic flux increases, the inclination of the magnetic field at the outer periphery of the sunspot increases accordingly. Thus, as the magnetic flux is accumulated to the spot, the field will be inclined more and becomes liable to be horizontal by downward magnetic pumping. This case is typical of penumbral formation.

It is interesting to note that the magnetic polarity is positive all over this particular area. While the northern periphery of the region, indicated by black arrows in figure 2, forms a penumbral structure, no penumbra is formed at the central part of the umbra, indicated by white arrows. The latter part is in the midst of a positive polarity area, and so the magnetic field will be nearly vertical even at the apparent boundary between the umbra and the normal photosphere, without forming a penumbral area.

2.2 Rapid emergence of magnetic field

Figure 3 shows the emergence of an EFR at the southern part of the region shown in figure 2. The EFR developed very rapidly in 10 hr. In the middle part of the EFR, penumbral structures were seen face to face in both polarities. Recent observations and numerical simulations show that the emerging magnetic flux stays horizontal for a while beneath the solar photosphere before emergence (Otsuji et al. 2011; Magara 2012; Toriumi & Yokoyama 2013). So we can expect that the magnetic field will be nearly horizontal in the middle part of the EFR, and manifested as photospheric dark lanes often observed in the middle part of EFRs (Otsuji et al. 2007). Furthermore, the EFR in question emerges at the bottom of a relatively older pre-existing bi-polar region and so the expansion of newly emerged magnetic flux to the higher layers will be suppressed. As the magnetic field is horizontal in the middle part of the EFR, the downward pumping mechanism is highly likely to work in this situation, leading to the formation of penumbral structure.

2.3 Appearance of twisted or rotating magnetic tube

Figure 4 shows a case of penumbral formation where a twisted or rotating magnetic tube appears in the photospheric surface. The apparent counter-clockwise rotation of the umbra continued for 5–6 hr. The situation might be explained by actual counter-clockwise field rotation or by the vertical emergence of a twisted field. In either case, the field will be inclined at the umbra/photosphere boundary.

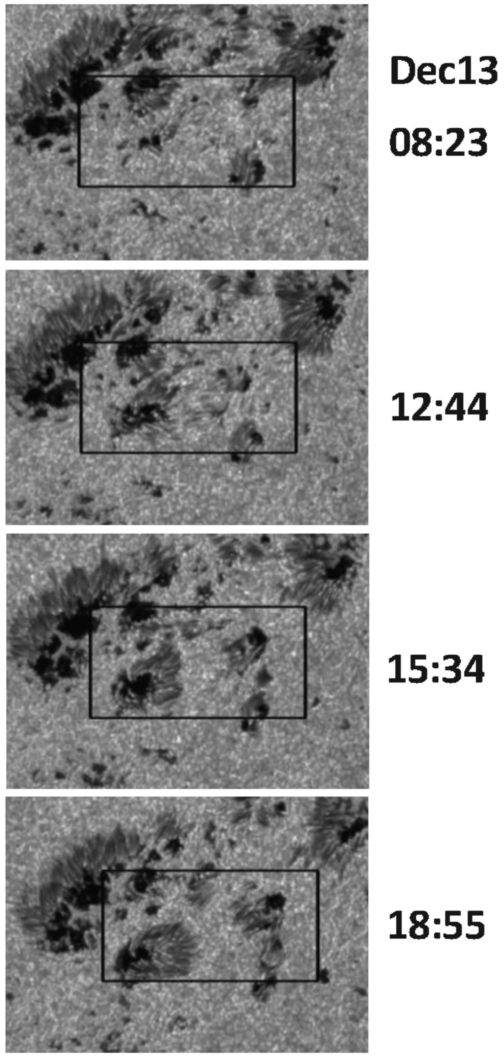

Fig. 3. Rapidly emerging magnetic flux region. Penumbral areas are seen in the middle part of both polarities. The FOV is about 95″ × 67″.

This can be seen from the non-radial pattern of the penumbral structure. So in this case, the magnetic field at the periphery of umbra is expected to be highly inclined and is liable to be affected by the magnetic pumping mechanism to form penumbral structure.

3 Discussion and conclusion

Thanks to the continuous observation by Hinode, we could morphologically follow the evolution of sunspots and found that there are a few different paths to penumbral formation: (1) active accumulation of magnetic flux, (2) rapid emergence of new magnetic flux, and (3) appearance of twisted or rotating magnetic tubes. In all of these cases, magnetic fields are expected to sustain high inclination at the edges of flux tube concentration longer than the characteristic growth time of downward magnetic pumping

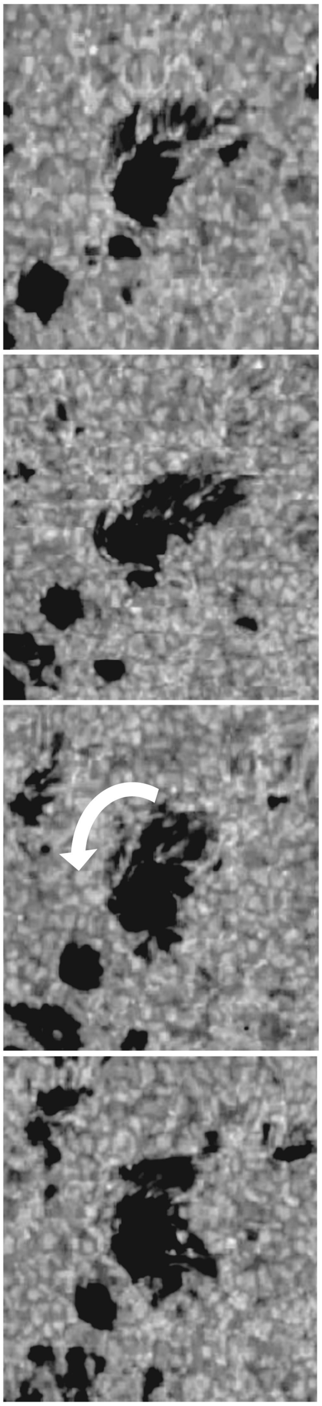

Fig. 4. Penumbral formation around a rotating or twisted magnetic tube. The umbra rotates counter-clockwise as is indicated by an arrow. The FOV is about 40″ × 45″.

(3–4 hr), which is estimated as 20 times the thermal diffusion time of photospheric convection (Tildesley & Weiss 2004).

As our report is only based on the morphological study, our findings must be confirmed by polarimetric observation of the three-dimensional magnetic field around penumbra-forming sunspots. Such an observation not only in the formation phases but also in the decaying phases of penumbrae is quite indispensable to clarify the detailed mechanism of penumbral formation.

Recently, such studies have been published by several authors. Penumbral formation in the preceeding spot of NOAA 11024 was studied by Schlichenmaier et al. (2010a, 2010b) and Rezaei, Bello González, and Schlichenmaier (2012) with spectro-polarimetric observation done at the German Vacuum Tower Telescope. The spot grew in area and in total magnetic flux through the merging of small flux patches. After a few hours of flux merging, a penumbral area was formed in the spot at the opposite side of the flux merging. They argue that the total magnetic flux attained a threshold for penumbral formation and the light bridge of the inclined magnetic field helped the penumbral formation. As they observed the relatively vertical magnetic field at the merging side and the inclined field at the opposite side, they suggested that these magnetic environments could control the actual penumbral formation. We think that the penumbral formation in NOAA 11024 is a case of active accumulation of magnetic flux and not a case of rapid flux emergence, and agree that the magnetic environment is a key factor in the actual penumbral formation, as we also notice the one-sided penumbra in figure 3.

Louis et al. (2013) analyzed the penumbral formation in NOAA 11283 with Hinode spectro-polarimetric observation. They found the coalescence of a pore with a decaying sunspot supplied enough magnetic flux and triggered the formation of penumbra at the location of the merger, not at the opposite side. We think that the penumbral formation in NOAA 11283 is basically a case of rapid flux accumulation. As the pore was a foot point of an active EFR, we suspect that rapid emergence may play a role in forming the penumbra at the merger side.

Romano et al. (2013) undertook spectro-polarimetric observation of NOAA 11490 and detected the status of the sunspot atmosphere just before the penumbral formation. They found a magnetic canopy structure at the chromospheric heights and uncombed photospheric magnetic structure in the spot atmosphere. We think that the penumbral formation there is also a case of active accumulation of magnetic flux forming a magnetic canopy structure of inclined magnetic field at the periphery.

Although these studies contribute much to our understanding of penumbral formation in the case of rapid flux accumulation, detailed behavior in the other cases of rapid flux emergence and rotating spots have not been fully observed yet. Further spectro-polarimetric observation of various cases will be necessary.

Acknowledgments

This work is partly supported by a Grant-in-Aid from the Japanese MEXT (No. 23540264). Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in cooperation with ESA and NSC (Norway).

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